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Constitutive Model for Rubberized Concrete Passively Confined with FRP Laminates

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ABSTRACT

This article develops an analysis-oriented stress-strain model for rubberized concrete (RuC) passively confined with fiber reinforced polymer (FRP) composites. The model was calibrated using highly instrumented experiments on 38 cylinders with high rubber contents (60% replacement of the total aggregate volume) tested under uniaxial compression. Parameters investigated include cylinder size (100×200mm or 150×300mm; diameter×height), as well as amount (two, three, four or six layers) and type of external confinement (Carbon or Aramid FRP sheets). FRP-confined rubberized concrete (FRP CRuC) develops high confinement effectiveness (f_{cc}/f_{co} up to 11) and extremely high deformability (axial strains up to 6%). It is shown that existing stress-strain models for FRP-confined conventional concrete do not predict the behavior of such highly deformable FRP CRuC. Based on the results, this study develops a new analysis-oriented model that predicts accurately the behavior of such concrete. This article contributes towards developing advanced constitutive models for analysis/design of sustainable high-value FRP CRuC components that can develop high deformability.

CE Database subject headings: Constitutive relations; Fiber reinforced polymer; Concrete; Composite Materials; Stress strain relations; Compression tests; Tire recycling

Author keywords: Rubberized concrete; Constitutive modeling; Passive confinement; Deformable concrete

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INTRODUCTION

The deformation capacity of reinforced concrete (RC) elements depends heavily on the compressive behavior of concrete and, specifically, on the capacity of concrete to develop large axial compressive strains (Paulay and Priestley 1992). The benefits that the lateral confinement of concrete sections can provide in terms of both overall strength and ductility enhancement have been demonstrated extensively, and this concept has been applied to strengthen existing structures (e.g. confinement of columns) as well as to develop innovative composite systems for new structural solutions (e.g. concrete-filled tubes). Although steel has been historically used to provide the required lateral confinement, fiber reinforced polymers (FRP) have been used extensively over the last 20 years as a strengthening solution to enhance the ultimate compressive strain of concrete cylinders (Mortazavi et al. 2003; Rousakis and Athanasios 2012; Spoelstra and Monti 1999) and deformability of columns (Garcia et al. 2014). Existing studies have also confirmed the potential of using FRP to fabricate the external shell of concrete-filled tubes and exploit the benefits of such a composite solution for the construction of new, high-performance structural elements (Becque et al. 2003, Ozbakkaloglu 2013, Zhang et al. 2015). Despite the demonstrated advantages of the lateral confinement of concrete, the inherent brittleness of concrete still imposes significant limitations on the performance of new structural elements and special solutions or components, such as complex reinforcement detailing (e.g. in coupling beams), bearings or base isolation systems, need to be used whenever high deformation demand is required.

Extensive research has examined the use of recycled tire rubber to produce rubberized concrete (RuC) in an attempt to further enhance the deformation capacity of concrete (Bompa et al. 2017; Ganesan et al. 2013; Li et al. 2004; Toutanji 1996). Rubber from end of life tires has high flexibility and can maintain its volume under compressive stress. However, when rubber is used to replace natural aggregates, both the compressive strength and the stiffness of the resulting concrete are expected to reduce as a function of rubber content. While the reduction in stiffness can be easily dealt with by appropriate dimensioning of section geometry and element size, the use of a high amount of rubber replacement (e.g. 100% sand replacement) can reduce the compressive strength of RuC by up to 90% (Batayneh et al. 2008), thus making RuC potentially unsuitable for structural applications. To recover the strength of RuC, yet maintain its desirable deformation capacity, recent studies have investigated the use of different types of confinement to produce confined rubberized concrete (CRuC). For example, Duarte et al. (2016) showed that rubberized concrete-filled cold-formed steel tubes improved the ductility of columns by up to 50% (rubber replacing 15% of the aggregate volume). Nevertheless, the steel confinement around RuC columns was less effective than that around conventional concrete columns with the same confinement. This was attributed to the lower expansion in RuC produced with such low rubber contents. Moreover, the RuC columns were more prone to local buckling. Youssf et al. (2014) examined the behavior of RuC-filled Carbon FRP (CFRP) tubes and observed an enhancement in cylinder compressive strength by 186% when using three CFRP confining layers and a 10% rubber replacement of aggregate volume. Similar results were reported by Li et al. (2011) from RuC (with 30% rubber replacing fine aggregate volume) cast in Glass FRP (GFRP) pipes, leading to an increase in compressive strength up to 5.25 times that of the unconfined rubberized concrete (RuC). While the above confinement led to some improvements in RuC strength, its influence on concrete deformability was limited when compared to conventional confined concrete (Lam and Teng 2004). This can be attributed to the relatively low amounts of rubber used in the aforementioned studies, which are insufficient to produce significant lateral dilation to activate the passive confinement pressure.

The inclusion of high volumes of recycled tire rubber in concrete is associated with various material and technological challenges, such as poor fresh properties (Flores-Medina et al. 2014; Güneyisi et al. 2004; Toutanji 1996; Medina et al. 2018). Research by the authors (Raffoul et al. 2016) has shown that some of these drawbacks can be overcome by optimizing the concrete mix parameters, leading to the development of RuC with high rubber content (>50% total aggregate content) and good workability, homogeneity and cohesiveness. More recent research (Raffoul et al. 2017) demonstrated that the external confinement of such RuC with three layers of Aramid FRP (AFRP) can lead to high strength (>75 MPa) and high deformability (axial strains >5%). This innovative FRP CRuC can be used for structural applications where high concrete deformability is required, e.g. plastic hinge zones or short columns. However, it is necessary to provide constitutive models suitable for the analysis and design of highly deformable elements. Using CRuC with high rubber contents, this article develops such a constitutive model for FRP CRuC.

This study begins with a description of the experimental program on 38 cylinders. In the following section, the experimental results are discussed in terms of the effect of confining material and pressure on the cylinders' stress-strain behavior. Based on the test results, a unified constitutive model to predict the stress-strain behavior of FRP CRuC is proposed. Concluding remarks of this study are given in the final section. This article contributes towards the development of analysis/design models so that FRP CRuC can be used for the development of highly deformable elements. The results presented in this study are part of the 7th Framework Programme EU-funded Anagennisi project which aims to develop solutions to reuse all tire components in high value innovative concrete applications (Pilakoutas et al. 2015).

EXPERIMENTAL PROGRAM

A total of 38 RuC cylinders confined with FRP jackets were subjected to axial compression. The main parameters investigated include the type of FRP material (Carbon or Aramid FRP), confinement pressure (number of FRP layers) and cylinder size (100×200mm or 150×300mm; diameter×height).

Materials

Concrete

All cylinders were cast with a concrete mix in which 60% of the fine and coarse aggregate volume was replaced with tire crumbs. Two batches were produced for this study. The selected mix was 'optimized' in a previous study (Raffoul et al. 2016) that minimized the adverse effects of large quantities of rubber on the fresh and hardened properties of RuC. The mix components for 1m^3 of RuC were: i) 340 kg of High strength Portland Limestone Cement CEM II–52.5 N (10-15% Limestone) conforming to (BS EN 197-1: 2011); ii) 42.5 kg of Silica Fume (SF) (Microsilica – Grade 940) and 42.5 kg of Pulverised Fuel Ash (PFA)

(BSEN 450–1, Class N Category B LOI); iii) two commercially available admixtures: 2.5 liters of Plasticiser (P) and 5.1 liters of Super Plasticiser (SP) (polycarboxylate polymers conforming to BS EN 934-2:2009); iv) 400.4. kg of Coarse Aggregate (CA): round river washed gravel (Sizes: 5-10 mm and 10-20 mm; Specific gravity: 2.65; Absorption: 1.24%), v) 328 kg of Fine Aggregate (FA): medium grade river washed sand (Sizes: 0-5 mm; Specific gravity: 2.65; Absorption: 0.5%, Fineness modulus: 2.64); and vi) rubber particles recycled through mechanical shredding of car and truck tires: 148.5 kg of Fine Rubber (FR) (sizes: 0-5mm) and 181.3 kg of Coarse Rubber (CR) (sizes 5-10mm and 10-20mm). The water to binder ratio (w/b) was set to 0.35. The rubber particles were selected to replace mineral aggregates of similar sizes. The mass of the rubber replacement particles was obtained considering a relative density of 0.80. Although the properties of the rubber were not directly examined and an inherent variability is expected, previous studies have confirmed that this has minimal effect on the properties of the resulting concrete (Raffoul et al. 2017). Table 1 presents average results from uniaxial compressive tests on three 100×200mm RuC control cylinders at 28 days.

Fiber Reinforced Polymer Jacket

To enhance the compressive strength of the RuC described above, a series of 100×200mm cylinders were externally confined with two, three or four layers of Carbon FRP (CFRP) or Aramid FRP (AFRP) sheets. The behavior of larger 150×300mm RuC cylinders confined using three or six CFRP or AFRP layers was also investigated to assess possible size effect. The number of confining layers for the larger specimens was determined according to Equation (1) to ensure a confining pressure equivalent to that given by two and four layers on the 100mm diameter cylinders. Equation (1) assumes that a) a uniform confinement pressure was applied across the cylinder section (circular geometry), and b) the force in the FRP was equal to the force resisted by the concrete core.

$$f_l = \frac{2nt_f}{D} f_f \qquad (1)$$

where f_l is the confinement pressure, n is the number of FRP layers, t_f is the thickness of one layer of FRP sheet, f_f is the tensile strength of the FRP fibers and D is the cylinder diameter.

At least five small cylinders were tested for each type and number of FRP layers, while two large cylinders were tested per parameter.

The FRP jackets consisted of unidirectional Aramid or Carbon fabrics embedded in an epoxy matrix. The FRP jackets were applied using the wet lay-up technique following the manufacturer's recommendations~~, which led to fiber volume fractions of 30%~~. The sheets were oriented perpendicular to the cylinder axis and overlapped by a length of 100 mm. Table 2 summarizes mean properties and corresponding standard deviation (SD) obtained from direct tensile tests on more than 30 FRP coupons (250 mm×15 mm×t_f), prepared as per BS EN ISO 527-5: 2009. In this table, t_f is the dry fiber thickness; f_f is the tensile strength; E_f is the modulus of elasticity; and ε_{fu} is the ultimate elongation of the FRP composite.

Experimental Setup, Instrumentation and Load Protocol

Figure 1 shows the typical test setup and instrumentation used for the tests. All specimens (confined or unconfined) were subjected to axial compression using a servo controlled ESH Universal Testing Machine of 1,000 kN capacity. The top and bottom of the specimens were confined using aluminum caps to avoid failure at the end zones of the cylinder due to stress concentrations (Kotsovos and Newman 1981). The caps were prepared as per ASTM standards (C1231M – 15). The caps were filled with gypsum, to allow cylinders to be tightly fitted within the caps and to be accurately leveled to minimize bending induced effects. Vertical strains were derived using vertical displacements. This was achieved by fixing two parallel aluminum rings (placed 100 mm apart) around the cylinders (Fig. 1b). The screws used to fix the aluminum rings were fitted with springs to allow lateral expansion of the cylinders without adding further confinement. During the tests, three vertical lasers (L1 to L3 in Fig. 2) mounted on the aluminum rings measured the shortening of the specimens at the center of the cylinders. To determine horizontal strains, the horizontal expansion was measured using a tensioned wire and a linear variable displacement transducer (LVDT) around the specimens' mid-height. Three horizontal (H) and two vertical (V) 10mm foil-type gauges measured local strains along the mid-height of the FRP jacket at the locations shown schematically in Fig. 2.

Two test protocols were applied: i) Monotonic loading at a displacement at a rate of 0.5 mm/min up to cylinder failure, and ii) consecutive sets of five unloading/reloading load cycles at increasing stress levels (+10 MPa/set) up to cylinder failure. A displacement rate of 0.5 mm/min was used for the first set of cycles, after which a rate of 2mm/min was used for all following loading and unloading cycles. At least two nominally identical small cylinders were tested monotonically, whereas three were subjected to cyclic load for each thickness and type of FRP. All large cylinders were loaded monotonically, and at least two cylinders were tested for each parameter.

The coupons were tested using a universal tensile testing machine of 300 kN capacity. All specimens were tested in tension under a monotonic displacement rate of 0.5mm/min. A 50mm gauge extensometer was mounted on the center of each coupon to measure its elongation and the data was recorded using a fully automated data acquisition system.

RESULTS AND DISCUSSION

Table 3 summarizes mean test results from the FRP CRuC specimens. The cylinders are identified according to the number of confining layers (2, 3, 4 or 6), confining material (A=AFRP or C=CFRP), loading type (M=monotonic or C=cyclic) and specimen number (1, 2 or 3). A letter (L) after the specimen number denotes the larger 150×300mm cylinders. For example, 3A-M1-L stands for specimen #1 of a large cylinder subjected to monotonic load and wrapped with three AFRP layers. Table 3 includes mean values (Avg) and standard deviations (SD) of: ultimate compressive strength (f_{cc}), ultimate axial (ε_{cc}) and lateral (ε_{ccl}) strains, confinement effectiveness (f_{cc}/f_{co}), ductility ($\varepsilon_{cc}/\varepsilon_{co}$), critical stress ($f_{cr}$), as well as the axial strain, lateral strain and Poisson's ratio at f_{cr} (ε_{cr}, ε_{lcr}, and ν_{cr}, respectively). Table 3 also shows the confinement stiffness (K_j) provided to each cylinder, calculated using equation (2).

$$K_j = \frac{2nt_f}{D} E_f \qquad (2)$$

Figure 3a provides a schematic presentation of the aforementioned parameters. The critical stress (f_{cr}) indicates the initiation of unstable crack propagation and concrete expansion, which activates the confining jacket leading to a significant change in the gradient of the curve, which depends on the FRP-jacket stiffness. The value of f_{cr} was defined as the inflection/pivot point of the CRuC secant modulus-stress relationship (E_{sec}-f_c) (Fig. 3b) at the minimum of its derivative function (dE_{sec}/df_c,) (Fig. 3c). This inflection point indicates a shift in the rate of stiffness degradation, which designates the activation of confinement pressure. Following careful examination of the results, f_{cr} was found to consistently occur when E_{sec} drops to around 70% of the confined concrete initial stiffness, which is comparable to the initial stiffness of unconfined concrete E_{co} (Fig. 3b). f_{cc}/f_{co} and $\varepsilon_{cc}/\varepsilon_{co}$ were calculated as the ratio of the ultimate stress and strain of the CRuC to the average peak stress (6.8MPa-8.2MPa) and peak strain (1350με) of the unconfined RuC cylinders, respectively. To accurately capture the initial deformations, axial strains between 0-A were taken from the two vertical strain gauges V1 and V2 that were more reliable during the initial stages of loading. This was also necessary since the resolution of the lasers L1-L3 was insufficient to capture accurately the initial axial deformations. After f_{cr} (point A), excessive localized bulging on the FRP jacket led to spurious strain gauge readings and therefore the axial strains from A-C were derived from the laser measurements. The horizontal strains were obtained from average readings from the horizontal gauges H1-H3 and corroborated using LVDT measurements of the wire. The results in Table 3 are discussed in the following sections.

Ultimate Condition and Failure Mode

All FRP CRuC specimens failed abruptly by tensile rupture of the FRP jackets (see Fig. 4). In all cases, FRP rupture initiated at approximately the mid-height of the specimens. Overall, the recorded FRP strains at cylinder rupture (ε_{ccl}) were below the failure tensile strains measured in the FRP coupons (ε_{fu}) (see Table 2 and Table 3). For instance, ε_{ccl} in AFRP-confined cylinders was around 70-80% of ε_{fu} of the AFRP coupons, while ε_{ccl} in CFRP-confined cylinders was 65-95% of ε_{fu} of the CFRP coupons. Premature rupture is also reported in previous studies (Lam and Teng 2004; Matthys et al. 2006) and can be attributed to local effects (non-homogeneous concrete deformations) leading to stress concentrations in the FRP, as well as to the effect of jacket curvature, overlap length and fiber misalignment.

Stress-Strain Behavior

Figures 5a-c and d-f compare the stress-strain behavior of AFRP CRuC and CFRP CRuC cylinders, respectively. The figures show individual stress-strain curves of monotonically loaded cylinders, the envelope of cyclically loaded cylinders (determined as shown in Fig. 3), as well as average curves for cylinders with similar FRP confinement. Although an in-depth analysis of the cyclic behavior of CRuC is outside the scope of this paper and the individual cycles are not reported to preserve clarity, the direct comparison of monotonic and cyclic results provides evidence that the monotonic behavior approximates well the envelope curve of the cyclically loaded specimens. This significant finding, which was previously confirmed for confined conventional concrete (Buyukozturk and Tseng 1984; Chang and Mander 1994; Lam et al. 2006; Osorio et al. 2013; Rousakis and Tepfers 2001), can allow the development of constitutive models capable of accounting for the full cyclic response of CRuC. The key parameters governing the cyclic behavior of CRuC, including the shape of its unloading/reloading curves, stiffness degradation, plastic deformation and energy dissipation, have been investigated by the authors ~~and are the subject of a~~ in a separate study~~future publication~~.

The results in Fig. 5a-c and d-f show that the axial and lateral stress-strain curves (both monotonic and cyclic envelope) are similar, and that the curves vary within the acceptable variability of the material. The data in Table 3 confirm that the ultimate stress and strain of specimens subjected to monotonic and cyclic load were similar. As expected, the stress-strain curves have an initial linear-elastic branch (controlled by the unconfined concrete behavior) until the critical stress f_{cr} (line 0-A in Fig. 3). This is followed by a transition curve (A-B in Fig. 3) and then a linear branch (B-C in Fig. 3) controlled by the expansion of the FRP, as discussed in a previous study by the authors (Raffoul et al. (2017)). Beyond f_{cr}, concrete cracking increases the cylinders' lateral expansion, thus activating the confinement progressively. As expected, higher confining pressure led to a steeper branch B-C.

Figures 6a-e provide a schematic presentation of the variation of the main curve parameters including critical stress (f_{cr}) and strain (ε_{cr}), Poisson's ratio (ν_{cr}), and confinement stress (f_{cc}/f_{co}) and strain effectiveness ($\varepsilon_{cc}/\varepsilon_{co}$), as function of confinement stiffness (K_j), respectively. The results in Fig. 6a-b and Table 3 indicate that an increase in K_j delays concrete cracking, which resulted in higher average f_{cr} and ε_{cr} for both AFRP and CFRP confinement. For example, at a confining stiffness of 975 MPa (2LA), the average f_{cr} and ε_{cr} were 10.7 MPa and 1580 με, respectively, while at a jacket stiffness of 1950 MPa (4LA), these values increased to 13.9 MPa and 2010 με, respectively. The effectiveness of FRP confinement on RuC is also confirmed by the ratios f_{cc}/f_{co} and $\varepsilon_{cc}/\varepsilon_{co}$. For RuC cylinders confined with four AFRP layers, f_{cc}/f_{co}=10 and $\varepsilon_{cc}/\varepsilon_{co}$=50. Comparatively, for conventional FRP-confined concrete with identical confining pressure, such values were only f_{cc}/f_{co}=4.2 and $\varepsilon_{cc}/\varepsilon_{co}$=18.5 (Jiang and Teng 2007; Lam and Teng 2003).

Figures 6a-c also show that the increase in f_{cr} due to increasing jacket stiffness was accompanied by a drop in lateral strain ε_{lcr} and, more notably, by lower Poisson's ratios (ν_{cr}) at f_{cr}. For example, ν_{cr} was approximately 0.42 for K_j=976 MPa (2LA) and it dropped to 0.30 for K_j=1952 MPa (4LA), indicating that the overall expansion was better controlled in the latter cylinder. Since the increase in Poisson's ratio can be used as an indicator of damage (Neville 1995), the above results indicate that increasing confinement stiffness delayed overall damage.

CFRP vs AFRP Confinement

Figure 7 compares the stress-strain behavior of AFRP and CFRP CRuC cylinders, normalized to the corresponding unconfined concrete strength (8.2 MPa and 6.8 MPa, respectively). Note that these results are the average of the individual curves respectively shown in Fig. 5a-c and d-f. The data in Fig. 7 clearly indicate that for the same number of CFRP or AFRP layers, CFRP jackets provided higher confinement pressure, which in turn led to a stiffer response in both axial and lateral directions after f_{cr}. This is due to the much higher stiffness of a CFRP jacket when compared to an AFRP jacket with the same number of layers (see Table 3).

The results in Table 3 also show that, in addition to the confining stiffness, the type of material also influenced the stress-strain behavior at f_{cr} and at the ultimate condition of CRuC. The rate of reduction in ν_{cr} and ε_{lcr} as a function of K_j was higher for AFRP CRuC cylinders than for CFRP CRuC cylinders. For example, for 3LA (K_j=1464 MPa), ν_{cr} was 0.31 and ε_{lcr} was 525με, whilst despite having a higher jacket stiffness, cylinders with 2LC (K_j=1665 MPa) exhibited higher Poisson's ratio (ν_{cr}=0.42) and higher lateral expansion (ε_{lcr}=895με) prior to f_{cr}. This indicates that the confining effect of AFRP activated earlier than in CFRP, thus limiting the RuC expansion more effectively in AFRP-confined cylinders. Similar results were observed for higher levels of CFRP confinement. For example, cylinders 3LC (K_j=2498 MPa) had higher ε_{lcr} and ν_{cr} (745με and 0.32, respectively) than cylinders 3LA (K_j=1464 MPa), even when the former had significantly higher jacket stiffness.

The effect of using different confining FRP material on concrete behavior has been previously discussed in the literature. Based on tests on conventional concrete cylinders confined with FRP, Dai et al. (2011), indicated that the efficiency factor (i.e. ratio of ε_{lcr} to ε_{fu}) is significantly higher for AFRP (around 0.93) than for CFRP (around 0.64). A similar trend was observed by Lim and Ozbakkaloglu (2014), who examined a large database of experimental data to show that the value of the FRP efficiency factor decreases as the modulus of elasticity of the fibers increased. Similar results were observed by Teng et al. (2009) when comparing GFRP to CFRP confined conventional concrete with identical confinement ratios. Despite the excellent performance of AFRP as confining material, existing studies on AFRP confined concrete are very limited (Dai et al. 2011; Ozbakkaloglu and Akin 2012; Lim and Ozbakkaloglu 2014) and even fewer studies compare the effectiveness of AFRP and CFRP confinement (Ozbakkaloglu and Akin 2012; Lim and Ozbakkaloglu 2014). Overall, the lower effectiveness of the CFRP compared to AFRP can be attributed to various reasons related to the physical and mechanical characteristics of the materials. These include: i) different initial pre-stress during the application of the fibers (due to the lower flexibility of the CFRP sheets), which leads to the CFRP sheet being less tightly wrapped around the cylinder and the presence of air voids; ii) higher stiffness in the CFRP, which can lead to higher axial load being transferred to the CFRP (transversally); iii) minor misalignment of the fibers; and iv) high interlaminar stresses at the FRP overlap, which could lead to a premature failure (Zinno et al. 2010). Nonetheless, a rational explanation of why the performance of AFRP/CFRP sheets with identical stiffness differs in confinement applications differs, remains elusive.

Size Effect

To investigate the effect of specimen size, Fig. 8a-b compare the stress-strain behavior of small (100×200mm) and large (150×300mm) cylinders with similar confining pressure. The data in Fig. 8 is normalized to the unconfined concrete strength, i.e. 8.2 MPa for the small cylinders confined with 2 or 4 layers of AFRP, and 6.8 MPa for all remaining cylinders cast from the same batch. The data in Fig. 8a-b show that no significant size effect was observed between 100x200mm and 150x300mm cylinders with identical confining pressure. For instance, the curves of the large cylinders (3L) are similar to those of the small cylinders (2L) with identical confinement pressure for both AFRP (Fig. 8a) and CFRP confinement (Fig. 8b). Although this is in line with previous results reported in the literature (Cui and Sheikh 2010). further investigation is required to assess the possible influence of specimen size on the confinement effectiveness in large cylinders or structural components.

Volumetric Behavior

To provide further insight into the mechanical behavior of FRP CRuC, Fig. 9 compares the average axial stress of the tested cylinders and their corresponding volumetric strains (ε_{vol}), which was calculated as:

$$\varepsilon_{vol} = 2|\varepsilon_{lat}| - |\varepsilon_{ax}| \qquad (3)$$

where ε_{lat} and ε_{ax} are the absolute lateral and axial strains measured during the tests, respectively. In equation (3), negative ε_{vol} values denote volumetric contraction. ε_{vol} is determined based on average stress-strain monotonic and cyclic curves of small (100×200mm) cylinders.

Figure 9 indicates that the CRuC cylinders experienced volumetric contraction at the initial elastic stage. Such behavior is expected and similar to that observed in conventional FRP-confined concrete (Jiang and Teng 2007; Papastergiou 2010). However, the volume of the cylinders also continued to reduce at levels of applied stress exceeding f_{cr}. This behavior is considerably different from that observed in conventional FRP-confined concrete, which typically expands at stress levels beyond f_{cr} (Jiang and Teng 2007; Lam and Teng 2003; Papastergiou 2010). The different behavior may be attributed to the "fluidity" of rubber particles, which possibly filled up the voids left by crushed/pulverized concrete. It should be noted that this behavior was also observed in a previous experimental study by the authors (Raffoul et al. 2017).

The experimental results from previous sections indicate that, compared to conventional FRP-confined concrete, FRP CRuC presents unique mechanical characteristics that need to be considered for the development of constitutive models. These include: i) higher stress and strain enhancement ratios (i.e. f_{cc}/f_{co} and $\varepsilon_{cc}/\varepsilon_{co}$, respectively); ii) larger cracking strain, thus increased f_{cr}; and iii) continuous volumetric contraction up to failure. The continuous volumetric contraction yields higher axial stress and strain at comparatively lower lateral strain than conventional concrete. As a result, much higher axial deformation can be achieved in CRuC before the ultimate strain capacity (rupture) of the FRP is reached. The following sections assess the accuracy of relevant existing models at predicting the ultimate condition of FRP CRuC. An active confinement model that predicts the stress-strain behavior of RuC confined with AFRP/CFRP sheets is then proposed.

MODELING OF FRP CRuC

Existing Analytical Models for FRP-Confined Concrete

Numerous studies have proposed design or analysis oriented models for conventional FRP-confined concrete. The latter models (Fardis and Khalili 1982; MC2010; Lam and Teng 2003; Miyauchi et al. 1999; Mortazavi 2003; Papastergiou 2010; Saadatmanesh et al. 1994; Jiang and Teng 2007; Toutanji 1999) are considered as more versatile as they a) can be modified to consider different confining materials, and b) can serve as the basis of simpler design-oriented models (Jiang and Teng 2007). To evaluate the accuracy of the above analysis-oriented models at predicting the ultimate strength and strain of FRP CRuC, Fig. 10 a and b compare the experimental results (Table 3) and model predictions of f_{cc}/f_{co}. In this figure, the amount of confinement is expressed as a mechanical volumetric confinement ratio ω_w (equation (4)) calculated using the ultimate lateral strains in the cylinders upon FRP rupture (ε_{ccl}), as proposed by Mortazavi (2003). Likewise, Fig. 11 a and b compare the experimental values to predictions of $\varepsilon_{cc}/\varepsilon_{co}$ as function of f_{cc}/f_{co}.

$$\omega_w = \frac{4nt_f}{D}\frac{E_f\,\varepsilon_{ccl}}{f_{co}} \qquad (4)$$

where all the variables are as defined before.

The results in Fig. 10 show that the models by Fardis and Khalili (1982), Lam and Teng (2003), Miyauchi et al. (1999) and Toutanji (1999) tend to overestimate the strength effectiveness of CRuC as a function of confinement ratio. This is especially evident for CFRP CRuC as can be seen in Fig. 10b. Conversely, Saadatmanesh et al. (1994) model underestimates f_{cc}/f_{co} for both AFRP and CFRP CRuC at all levels of confinement. It is also shown that Papastergiou (2010), Mortazavi (2003) and MC2010 (2010) models predict satisfactorily the ratios f_{cc}/f_{co} only for heavy AFRP confinement (ω_w>4). Overall, none of the aforementioned models can predict satisfactorily the values of both f_{cc}/f_{co} and $\varepsilon_{cc}/\varepsilon_{co}$ for FRP CRuC.

Proposed Model

Based on regression analyses of the experimental results, a new model for FRP CRuC is proposed in the following. The model is based on the active confinement model by Mander et al. (1988) (which is a modified version of Popovics (1973) equations), and on a refined version of an incremental iterative procedure based on lateral-to-axial strain relationships proposed by Papastergiou (2010). The model by Mander et al. (1988) was originally developed for steel confined concrete and consists of a family of axial stress-strain curves at different values of constant lateral confinement pressure applied to the concrete core. The stress-strain curves can be determined using equations (5) to (7).

$$f_c = \frac{f_{cc,\omega} x r}{r - 1 + x^r} \tag{5}$$

where

$$x = \frac{\varepsilon_c}{\varepsilon_{cc,\omega}} \tag{6}$$

$$r = \frac{E_{co}}{E_{co} - E_{sec,\omega}} \tag{7}$$

where $f_{cc,\omega}$ and $\varepsilon_{cc,\omega}$ represent the ultimate compressive strength and corresponding strain of the actively confined concrete and $E_{sec,\omega}$ is the secant modulus ($f_{cc,\omega}/\varepsilon_{cc,\omega}$) for the corresponding confinement ratio (ω_{wi}).

The lateral strain of the FRP jacket was determined following general equation (8) proposed by Papastergiou (2010) :

$$\varepsilon_l = \left(\frac{1}{b} \left(\frac{E_{co} \varepsilon_c}{f_c} - 1 \right)^a + \nu \right) \frac{f_c}{E_{co}} \tag{8}$$

where a and b are empirically calibrated factors, and ν is the concrete (initial) Poisson ratio.

Based on the equations above, the accurate prediction of $f_{cc,\omega}$, $\varepsilon_{cc,\omega}$, a and b is key in establishing a reliable characterization of lateral-to-axial strain relationships (i.e. the relationship between ε_l and ε_c), which is essential to develop a model that can accurately capture the behavior of CRuC confined with different amounts of FRP.

The following sections provide a brief description of the procedure used to determine the above parameters.

Axial stress and strain at peak stress

A regression analysis of the experimental results was used to capture the strength and strain enhancement ratios (i.e. $f_{cc,\omega}/f_{cr}$ and $\varepsilon_{cc,\omega}/\varepsilon_{cr}$) at different confining pressures. These ratios form the basis of the active confinement model (equations 5-7) and are varied as function of the confinement ratio (ω_W) at each iteration (see iterative procedure below).

The ultimate compressive strength ($f_{cc,\omega}$) at each AFRP/CFRP confining ratio can be calculated using equation (9).

$$f_{cc,\omega} = f_{cr}(1.06\beta\omega_{wi} + 1.25) \quad (9)$$

The ultimate strain at peak stress ($\varepsilon_{cc,\omega}$) may be predicted for AFRP and CFRP using equation (10).

$$\varepsilon_{cc,\omega} = \varepsilon_{cr}\left(4.7\left(\frac{f_{cc,\omega}}{f_{cr}} - 1.25\right)^{1.2} + 1.5\right) \quad (10)$$

where f_{cr} and ε_{cr} are the critical stress and strain, respectively and β is an effectiveness factor, determined as follows.

To capture the elastic behavior and the increase in f_{cr} with increasing jacket stiffness, this model uses f_{cr} (as opposed to f_{co} as used in Jiang and Teng (2007), Papastergiou (2010) and Toutanji (1999)) to determine the strength and strain enhancement ($f_{cc,\omega}/f_{cr}$ and $\varepsilon_{cc,\omega}/\varepsilon_{cr}$, respectively) at different confining levels. This is due to the fact that, unlike conventional confined concrete, the onset of cracking in CRuC occurs at a relatively higher load (thus increasing the elastic region), which leads to a much higher f_{cr} relative to the elastic stress of the unconfined concrete (f_{co}), as observed in previous research (Raffoul et al. (2017)).

Based on calibration with test data, the variation in f_{cr} as a function of f_{co} and normalized confinement stiffness K_{jn} was determined using equation (11), whereas ε_{cr} was determined as function of K_{jn} as shown in equation (12).

$$f_{cr} = f_{co}\left(-6.5x10^{-6}K_{jn}^{2} + 5.8x10^{-3}K_{jn} + 0.8\right) \quad (11)$$

$$\varepsilon_{cr} = \varepsilon_{co}\left(-5.2x10^{-9}K_{jn}^{2} + 5.2x10^{-6}K_{jn} + 0.0011\right) \quad (12)$$

where K_{jn} is determined as follows:

$$K_{jn} = \beta\frac{2nt_f}{D}\frac{E_f}{f_{co}} \quad (13)$$

where β is an effectiveness factor (calibrated with test data) that accounts for the effect of the type of confining material on the critical and ultimate stress-strain behavior of CRuC (described in section "CFRP vs. AFRP confinement"). Based on the experimental data, β was found to be 0.75 for CFRP and 1.0 for AFRP confined cylinders, thus indicating a 25% reduction in the effectiveness of the CFRP compared to AFRP with identical confining stiffness.

Lateral to axial stress-strain relations

The value of ε_l (equation (8)) has a significant influence on the gradient of the linear part of the stress-strain relationship (slope of line B-C in Fig. 3) and it also controls the convergence of the model. Based on single and multiple objective genetic algorithm optimization (Chipperfield and Fleming 1995), the optimal combination of a and b to fit the experimental data of the average plots for all levels of AFRP/CFRP confinement was obtained. The optimization function criterion was to minimize the error between the experimental and predicted curves in terms of the area under the curves (both lateral and axial stress-strain curves) as well as the ultimate conditions for 2,3 and 4 layers of AFRP and CFRP simultaneously. Based on the optimization analysis, a constant value of a=1 was found suitable for all of the tested configurations. The resulting values of b were found to vary with confining jacket stiffness. As such, equation (14) was developed to describe the variation of b with K_{jn} and account for the effect of multiple confining layers and different FRP material.

$$b = 2.15 + 0.0045 K_{jn} \tag{14}$$

Iterative procedure

The proposed analytical model assumes that at a given confinement ratio (ω_{wi}), concrete with either passive or active confinement exhibits similar axial stress and strain values (Jiang and Teng 2007; Papastergiou 2010). Accordingly, the axial stress (f_c) for the FRP-confined cylinders at a given axial strain (ε_c) and confining pressure (ω_{wi}) can be determined using the following iterative procedure:

1. An initial value of axial strain (ε_c) is imposed (for example, ε_c = 500με).
2. A small initial confining ratio is assumed (ω_{wi}=0.001). The corresponding ultimate stress ($f_{cc,\omega}$) and ultimate strain ($\varepsilon_{cc,\omega}$) for the current ω_{wi} are calculated using equations (9) and (10), respectively.
3. At the assumed confining pressure, the axial stress f_c is determined using the base active confinement model (equation (5)).
4. The lateral strain (ε_l) is calculated using equation (8) and the corresponding confinement ratio (ω_{wf}) is determined using equation (4), where ε_{ccl} is substituted with the lateral strain of the corresponding iteration (ε_l). If ω_{wf} coincides with the initial confinement ratio (ω_{wi}) applied in step 2, then f_c and ε_c (determined in steps 3 and 1, respectively) correspond to a point on the predicted stress-strain curve of the FRP-passively confined concrete. Otherwise, steps 2 to 4 are repeated using the updated confinement ratio (ω_{wf}) until the two ratios converge.

5. The above steps are then repeated with an incremental increase in ε_c to generate the full stress-strain curve for FRP CRuC. The incremental process ends when the lateral failure strain (ε_{ccl}) of the FRP confinement is reached (refer to values in Table 3).

Model Predictions

Figures 12 a and b compare the curves predicted by the proposed model and the average experimental results for AFRP and CFRP CRuC cylinders, respectively. The results indicate that, in general, the model predicts well the average initial stiffness, critical stress and strain, gradient of the curve and the ultimate stress and strain values of the tested cylinders.

Figures 13 a and b compare the test results and the predictions of the main curve parameters (ultimate conditions f_{cc}/f_{cr} and $\varepsilon_{cc}/\varepsilon_{cr}$, respectively). Fig. 13a-b include data from individual cylinders as well as the average data used to calibrate the predictive model equations in the previous section. It must be noted that the model overestimates f_{cc}/f_{cr} and $\varepsilon_{cc}/\varepsilon_{cr}$ for CRuC with light AFRP confinement (2LA), while it underestimates these values for heavy CFRP confinement (4LC). This slight discrepancy is attributed to the difficulty of achieving a unified model with a regression that fits perfectly all levels of confinement. An accurate prediction of the ultimate conditions (f_{cc} and ε_{cc}) requires a simultaneously accurate prediction of the stress and strain at peak (f_{cr} and ε_{cr}), which is difficult to achieve. The high standard deviation (compared to typical concrete) can be attributed to the higher variability of aggregate distribution, but also to the fact that the standard deviation is calculated for a ratio (e.g. $\varepsilon_{cc}/\varepsilon_{cr}$), which effectively implies that any error in the prediction of either value further increases the value of deviation. Additional experimental datasets can be useful to further calibrate values of f_{cc}/f_{cr} and $\varepsilon_{cc}/\varepsilon_{cr}$ for CRuC. Overall, however, the predictions of ultimate conditions are within the expected variability of the individual test data (see Fig. 13 and Table 3), with an average standard deviation of 18% for f_{cc}/f_{cr} and 35% for $\varepsilon_{cc}/\varepsilon_{cr}$.

It should be noted that the proposed model is only applicable for high rubber contents as those used in this study (60% aggregate volume replacement). To date, research on CRuC with high rubber contents is not available in the literature, and therefore further research is necessary to validate the accuracy of the model using other experimental datasets and to extend the model to other rubber contents. Future research should also extend the applicability of the proposed model to other widely available confining materials (such as Glass or Basalt FRP) as well as evaluate the use of internal reinforcement (such as closely spaced stirrups) for confining RuC in applications where high compressive effectiveness is not required. The lower effectiveness observed in CFRP CRuC also requires further investigation. Experimental and analytical work on the cyclic behavior of highly-deformable structural elements made with FRP CRuC has also been conducted by the authors and will be reported in future publications.

CONCLUSIONS

This article proposes a new analysis-oriented stress-strain model for rubberized concrete (RuC) confined with FRP composites. The model is calibrated using test results from monotonically and cyclically loaded RuC cylinders confined externally with 2, 3, 4 or 6 layers of AFRP or CFRP sheets. Based on the results of this study, the following conclusions can be drawn:

1) FRP-confined RuC (FRP CRuC) made with high rubber volumes (>60% of aggregate replacement) can develop high compressive strength (up to 100 MPa) and very high deformations (axial strains of 6%). This innovative concrete can be used to build strong and highly deformable RC components for structural applications.
2) The confining effect of FRP activates earlier in FRP CRuC than in conventional FRP-confined concrete, which in turn leads to enhanced strengths and strains in FRP CRuC (enhancement ratios of 11 and 45, respectively). The better effectiveness of the confinement can be attributed to the large initial lateral strains in the RuC used in this study, which activates the FRP early. Whilst the confinement was very effective in enabling the development of high strength and deformability, the initial stiffness of CRuC is similar to the stiffness of unconfined RuC (around 10 GPa). Depending on the applications of CRuC, serviceability issues arising from its low stiffness as well

as its shortening (at f_{cc}) may be resolved by design, e.g. section size or geometry, so as to maintain adequate stiffness at serviceability limit states, yet develop enhanced deformation capacity and energy dissipation at ultimate limit states.

3) The test results confirm that, unlike conventional FRP-confined concrete, the volume of the FRP CRuC cylinders tested in this study undergoes continuous contraction. An increase in the stress at cracking (f_{cr}) was also observed. Such behavior needs to be considered in the development of constitutive relations of CRuC.
4) The use of CFRP confining sheets led to lower strengths and strain effectiveness when compared to AFRP sheets with identical confining jacket stiffness. Future research should investigate the reasons behind this behavior.
5) Existing stress-strain models for conventional FRP-confined concrete cannot predict the behavior of the tested FRP CRuC cylinders. The new analysis-oriented model proposed in this study predicts well the stress-strain relationships of both AFRP and CFRP CRuC (average standard deviation for predictions of the ultimate conditions <5%). However, future research should validate the accuracy of this model using other experimental datasets and different types of FRP (e.g. glass or basalt FRP sheets).
6) The model proposed in this study can be used to predict the envelope curve of CRuC subjected to a series of unloading and reloading cycles and provides a first step towards defining its full cyclic constitutive stress-strain behavior.

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NOTATION

The following symbols are used in this paper:

D = cylinder diameter;

E_{co} = concrete initial modulus of elasticity;

E_f = FRP tensile modulus of elasticity;

E_{sec} = secant modulus of elasticity of concrete at various stress and strain values;

$E_{sec,\omega}$ = secant modulus of actively confined concrete (at $f_{cc,\omega}$ and $\varepsilon_{cc,\omega}$) for the corresponding ω_w;

f_c = axial compressive stress in confined/unconfined concrete;

f_{co} = compressive strength of unconfined concrete;

f_{cc} = compressive strength of confined concrete;

$f_{cc,\omega}$ = ultimate compressive stress of actively confined concrete at corresponding ω_w;

f_{cr} = critical stress;

f_l = lateral confinement pressure;

f_f = tensile strength of the FRP coupon;

K_j = FRP jacket stiffness;

K_{jn} = FRP jacket stiffness normalized to the unconfined concrete strength;

n = number of layers of FRP confinement;

t_f = thickness of one layer of FRP sheet;

β = FRP confinement effectiveness factor;

ε_{ax} = cylinder axial strain (in absolute value);

ε_c = axial strain in confined/unconfined concrete in compression;

ε_{cc} = ultimate axial strain in FRP confined concrete in compression;

$\varepsilon_{cc,\omega}$ = ultimate axial strain in actively confined concrete at corresponding ω_w;

ε_{ccl} = ultimate hoop lateral strain in FRP confined concrete in compression;

ε_{co} = axial strain at peak stress in the unconfined concrete;

ε_{cr} = axial strain in FRP confined concrete at critical stress;

ε_{fu} = ultimate elongation of FRP coupons (in direct tension);

ε_l = lateral strain in confined concrete at different levels of stress;

ε_{lat} = cylinder lateral strain (in absolute value);

ε_{lcr} = lateral strain in FRP confined concrete at critical stress;

ε_{vol} = volumetric strain;

ν = initial Poisson's ratio;

ν_{cr} = Poisson's ratio at critical stress; and

ω_w = mechanical volumetric confinement ratio;

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Table 1. Mean mechanical properties of RuC at 28-days

Compressive strength (MPa)		Strain at peak strength (με)		Modulus of elasticity (GPa)	
Mean	SD	Mean	SD	Mean	SD
7.6	1.3	1350	200	10.3	1.8

Table 2. Mechanical properties of FRP jackets based on direct tensile coupon tests

Fiber type	No. of layers	t_f (mm)	f_f (MPa)	$f_{f, AVG}$ (MPa)	E_f (GPa)	$E_{f,AVG}$ (MPa)	ε_{fu} (%)	$\varepsilon_{fu,AVG}$ (%)
Aramid	2L	0.40	2410	2430 (260*)	116	122 (16*)	2.08	2.06 (0.11*)
	3L	0.60	2705		140		1.94	
	4L	0.80	2180		110		2.16	
Carbon	2L	0.37	2040	2065 (80*)	242	225 (12*)	0.84	0.90 (0.07*)
	3L	0.56	2000		220		0.88	
	4L	0.74	2150		220		0.98	

*Standard Deviation

Table 3. Main test results from cylinders

ID	K_j (MPa)	f_{cc} (MPa)	Avg (SD)	f_{cr} (MPa)	Avg (SD)	ε_{cc} (%)	Avg (SD)	ε_{cr} (%)	Avg (SD)	ε_{ccl} (%)	Avg (SD)	ε_{lcr} (%)	Avg (SD)	v_{cr}	Avg (SD)	f_{cc}/f_{co} (Avg)	$\varepsilon_{cc}/\varepsilon_{co}$ (Avg)
2A-M1		39.9		8.1		3.78		0.102		1.42		0.040		0.39			
2A-M2		44.6		8.7		4.60		0.116		1.93		0.033		0.28			
2A-C1	976	39.5	40.1 (2.8)	11.7	10.7 (2.2)	4.16	3.90 (0.48)	0.221	1580 (485)	1.51	1.55 (0.22)	0.067	665 (305)	0.32	0.36 (0.08)	5.9 (0.4)	28.9 (3.6)
2A-C2		39.6		12.9		3.40		0.201		1.44		0.093		0.46			
2A-C3		37.0		12.1		3.58		0.161		1.44		-		-			
3A-M1		73.5		12.8		4.97		0.125		1.62		0.052		0.42			
3A-M2		66.2		11.2		5.51		0.162		1.40		0.065		0.40			
3A-C1	1464	70.2	69.9 (2.6)	18.6	13.5 (3.1)	4.96	5.41 (0.45)	0.273	1800 (555)	1.29	1.57 (0.24)	0.054	525 (80)	0.20	0.31 (0.09)	8.5 (0.3)	40.1 (3.4)
3A-C2		69.8		11.2		6.02		0.183		1.90		0.049		0.27			
3A-C3		69.6		13.7		5.61		0.159		1.62		0.043		0.27			
4A-M1		101.4		15.3		7.25		0.272		1.80		0.065		0.24			
4A-M2		90.7		13.6		5.56		0.237		1.39		0.070		0.30			
4A-C1	1952	89.8	92.5 (5.0)	11.6	13.9 (1.8)	5.49	6.05 (0.76)	0.170	2010 (510)	1.61	1.63 (0.15)	0.045	580 (140)	0.26	0.30 (0.07)	11.3 (0.6)	44.8 (5.6)
4A-C2		90.1		13.0		6.36		0.158		1.71		0.041		0.26			
4A-C3		90.3		16.1		5.58		0.167		1.64		0.070		0.42			
3A-M1-L	976	36.1	36.3 (0.3)	9.9	9.8 (0.2)	3.42	3.33 (0.1)	0.196	1550 (590)	1.46	1.43 (0.0)	0.062	525 (135)	0.32	0.35 (0.05)	5.3 (0.0)	24.7 (0.9)
3A-M2-L		36.5		9.6		3.24		0.113		1.40		0.044		0.38			
6A-M1-L	1952	73.7	73.0 (1.1)	16.2	13.6 (3.7)	6.03	5.78 (0.3)	0.265	2495 (220)	1.20#	1.53# (0.5)	0.073	685 (55)	0.27	0.28 (0.01)	10.7 (0.2)	42.9 (2.6)
6A-M2-L		72.2		11.0		5.54		0.234		1.86		0.065		0.28			

2C-M1		33.6		11.2		2.69		0.160		0.74		0.073		0.45			
2C-M2		29.8		11.4		1.73		0.181		0.62		0.063		0.35			
2C-C1	1665	34.2	33.1 (2.4)	11.4	12.0 (1.0)	1.96	2.30 (0.47)	0.159	2150 (695)	0.79	0.76 (0.10)	0.069	895 (305)	0.43	0.42 (0.07)	4.9 (0.4)	17.1 (3.4)
2C-C2		36.0		12.4		2.83		0.316		0.90		0.110		0.35			
2C-C3		31.7		13.6		2.30		0.259		0.73		0.133		0.51			
3C-M1		46.4		-		2.56		-		0.75		-		-			
3C-M2		51.2		16.0		2.63		0.292		0.85		0.100		0.34			
3C-C1	2498	49.9	49.3 (2.0)	13.3	12.3 (3.2)	3.20	2.82 (0.65)	0.193	2250 (685)	0.88	0.82 (0.20)	0.072	745 (320)	0.37	0.32 (0.07)	7.3 (0.3)	22.4 (3.9)
3C-C2		49.6		11.6		3.69		0.270		1.09		0.097		0.36			
3C-C3		28.6#		8.4		2.00#		0.145		0.58#		0.030		0.21			
4C-M1		63.7		15.4		4.07		0.275		0.85		0.059		0.21			
4C-M2		61.6		15.4		3.24		0.214		0.81		0.058		0.27			
4C-C1	3330	49.9	59.8 (6.3)	16.7	14.5 (1.9)	3.01	3.57 (0.56)	0.235	2305 (270)	0.55	0.77 (0.19)	0.080	550 (175)	0.34	0.24 (0.07)	8.8 (0.9)	26.4 (4.1)
4C-C2		57.9		12.4		3.26		0.206		0.61		0.034		0.17			
4C-C3		66.1		12.8		4.26		0.222		1.02		0.044		0.20			
3C-M1-L	1665	29.6	30.2 (0.9)	11.4	12.1 (1.0)	1.96	2.05 (0.1)	-	-	0.48	0.58 (0.1)	0.080	735 (88)	-	-	4.4 (0.1)	15.2 (1.0)
3C-M2-L		30.8		12.8		2.15		0.261		0.68		0.068		0.26			
6C-M1-L	3330	58.0	58.8 (1.2)	14.1	14.2 (0.2)	3.19	3.35 (0.2)	0.213	2470 (480)	0.87	0.78 (0.1)	0.069	695 (10)	0.32	0.29 (0.05)	8.7 (0.2)	24.8 (1.7)
6C-M2-L		59.7		14.4		3.51		0.281		0.70		0.071		0.25			

Premature failure of test set-up or instrumentation